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Developing and Applying the Water Supply Simulation Model

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Developing and Applying the Water Supply Simulation Model

Robert M. Clark and Richard M. Males

The Water Supply Simulation Model is a series of computer programs that allows for evaluation of the physical and economic characteristics of a water distribution system in a spatial framework. Development of the model and its application to the water supply system of the village of New Vienna, Ohio, are described.

Passage of the Safe Drinking Water Act has intensified interest in problems related to water supply and water utility management. Analysis of the regulations to be promulgated under the act indicates that some water utilities, particularly small ones, may be adversely affected economically.[1] An often-suggested option is that small systems combine with a larger system to form a regional water supply utility. It is assumed that the economies of scale associated with a regional water system would benefit the customers of small systems.

A characteristic of many production and transportation problems is the trade-off between the cost of building and operating facilities to meet demands for a product and the cost of transportation.[2] High transportation costs and low facility costs indicate decentralization; the reverse situation indicates a few large central facilities. These costs must be considered in planning, designing, constructing, and operating water supply systems.

It is possible to separate the water supply system physically into two components: (1) the acquisition and treatment function, and (2) the delivery (transmission and distribution) system.[3] Each of these components has a different cost function. The unit costs associated with treatment facilities are usually assumed to decrease as the quantity of service provided increases. The delivery system, however, is more directly affected by the characteristics of the area being served. The cost tradeoffs between the two components determine the cost of delivering water to any portion of the service area.

Because few analytical instruments are available for study of the economics of water supply systems, the US Environmental Protection Agency's Drinking Water Supply Research Division initiated a program to develop techniques and methodologies to evaluate the economics of regional systems. This article describes the development of a simulation model designed to aid in such an evaluation. The model can also provide insights into other water-related economic issues, such as spatial pricing and costing, conservation policies, operating improvements versus increased capital expenditure, user class subsidization, and fire protection capacity.

The model, called the Water Supply Simulation Model (WSSM), incorporates a series of submodels to describe the various economic, demographic, and hydraulic aspects of a water utility.

Model structure

The WSSM (Figure 1) is based on the concept of a water utility as a network providing service to a series of demands that are spatially distributed. The model can be used to analyze the costs of delivering water to these demand points. The service network is modeled as a link-node network, and it is assumed that water enters and leaves the system only at the nodes, which represent treatment plants, junctions, demand locations, and storage tanks. Water is carried between the nodes through connecting links (pipes). Costs are allocated to the various facilities and system components based on the amount of flow carried by that component.

The WSSM therefore requires that the water delivery and treatment system be described as a network of pipes, storage tanks, treatment plants, demands, and other hydraulic elements. Information concerning the network is stored in a network data base, including descriptive or calculated information about each element, such as size of pipe, geographic location of each demand, population associated with a demand, and connectivity of pipes (how one pipe is connected to another).

As a data base management system, the WSSM utilizes files that are permanently stored, as opposed to "decks" of data cards. The items of primary interest are the nodes and links of the distribution system. Two files are maintained—the node file, containing records for each node, and the link file, containing records for each link. The nodes and links define the network, and they are numbered as shown in Figure 2. The individual node and link numbers (identifiers or IDs) correspond to individual records in the link and node files. All records in a file are structured in the same general fashion (Figure 3).

The seven software modules used in the model are the establishment module, the editing module, the display module, the listing module, the hydraulic analysis module, the system solver module, and the input-output (I-O) module (Table 1). Establishing a data base for the WSSM requires the use of four of these modules.

TABLE 1
Major elements of WSSM

Element	Description
Network data base	Separate but cross-referenced data for the link and nodal elements of the network
	Standard and user-specified data items
Data base access methods	Routines designed for efficiency and ease of use Routines in standard FORTRAN, not strongly tied to a particular computer
Hydraulic network analysis model	Nonproprietary WATSIM model with both steady-state and dynamic simulation capabilities and ability to model a wide range of hydraulic elements
Other physical and economic models	Linear cost allocation procedure
	General purpose physical system solver to solve problems involving multiple sources, travel time, and mixing at nodes
Display and reporting modules	General purpose listing programs for link and nodal elements
	Flexible pen plotter display program for producing annotated maps of network
Data base establishment and edit modules	Establish comprehensive link and node files and check and cross-reference information in the two files, thus maintaining topological integrity of the network

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The establishment module prepares a list of possible errors while creating the files, but no corrections to the input data are made. The display and listing modules are then used to verify the contents of the files, and necessary corrections are made with the editing module. Because of the importance of the integrity of the topologic and geographic information in the files, all modules except the key establishment and editing modules are designed to preclude destruction or distortion of these data.

The hydraulic module performs steady-state hydraulic network analysis, defining flow and pressure, given demands. The current version of WSSM uses WATSIM as the basis of the hydraulic module.[4]

The solver module is a general purpose algorithm that sets up and solves problems related to mixing in networks, given the network topology and flows. It is used with WSSM to solve three types of problems: (1) determining the travel time for any source to a node; (2) determining the concentration of any constituent at any node, given the concentration of the constituent at all sources; and (3) determining the cost of delivered water at any node, given the individual annual costs associated with the nodes and links of the system.

Both the solver and hydraulic analysis modules have the capacity to reinsert data into the data base, where they can be used for further calculation, listing, or graphical display.

The original concepts and approaches of the model were tested in a pilot study of the Cincinnati, Ohio, Water Works system. Figure 4 shows a contour map of various cost zones within the service area, which was developed from a pilot version of the WSSM. This approach allowed analysis and display of complex physical, policy, and economic situations and encouraged further development of the WSSM. A revised, more-general-purpose version of the model has been created, using the New Vienna, Ohio;[6] Kenton County, Ky.; and Tampa, Fla., water systems as "test-beds."

The New Vienna system

New Vienna is a village of approximately 1000 people (1980), located in Clinton County in the southwestern part of Ohio (Figure 5). The water supply system serves approximately 900 people and incorporates some 340 residential meters. Light industry, laundromats, and schools are also served by the system. The average metered use in the village is approximately 1.7 mil gal (6.4 ML) per month.

Water is supplied to the system from two sources: a well field and treatment plant, operated by the village, and purchased water from Highland County. Because the village is required to purchase a set amount of water each month from Highland County, it uses that water before switching over to its local sources. In a typical month, two thirds of the water is purchased.

The distribution system, which dates back to 1903, consists of pipes 8 in. (200 mm) and less in diameter, with the majority of pipes in the system being 4 in. (100 mm). A single elevated storage tank, with a capacity of 50 000 gal (189 270 L), provides load leveling and minimal fire protection. Plans are under development to provide additional storage. Operation of the system (Figure 6) is based on the water level in the elevated storage tank. Pumping starts at a pressure of 47 psig (324 kPa) and stops at 52 psig (358 kPa).

Elevations in New Vienna range from 1110 ft (338 m) to 1180 ft (360 m). The average total head for the system is approximately 1240 ft (378 m). Low pressures of about 23 psig (158 kPa) exist at the higher elevations during normal operations, but during fire fighting, pressures may drop to as low as 0 to 12 psig (0 to 82 kPa) in certain areas.

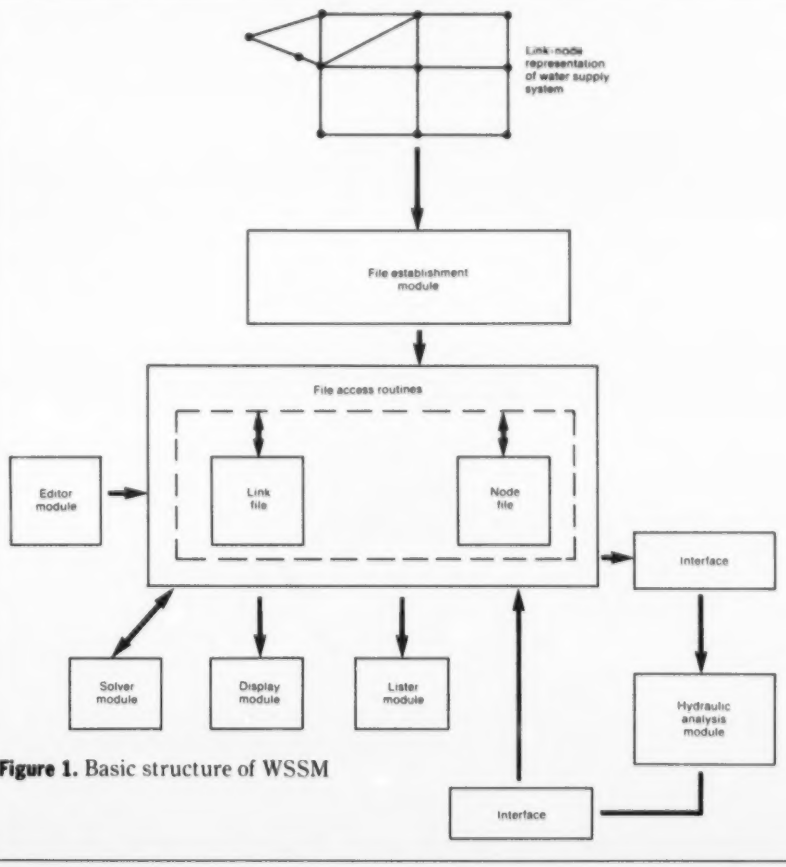

Figure 1. Basic structure of WSSM

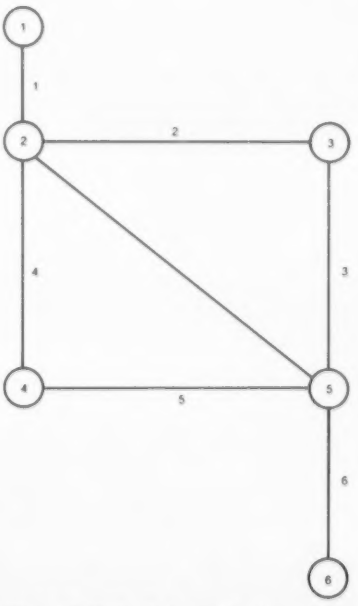

Figure 2. Node-link numbering scheme

Data base development

Development of the New Vienna data base consisted of the following steps:

- delineation of the distribution system in link-node form;
- determination of physical characteristics, for example, pipe size, and spatial coordinates;
- development of demand data; and
- development of cost data.

There is, of necessity, some interplay among these efforts to ensure that the link-node representation portrays the important changes in physical character of the system.

Delineation of system in link-node form. A link-node representation of the New Vienna water system was laid out on a gridded overlay to the base map (1 in. = 200 ft). Nodes were located in continuous lengths of pipe, based on their serving as centers of demand. Nodes were also located at pipe junctions and at changes in pipe diameter or type. To provide an accurate geometric as well as topographic map of the system, nodes were also located at major changes of pipe direction. Links and nodes were numbered sequentially. The New Vienna link-node representation consists of approximately 50 links and 50 nodes.

Determination of physical and spatial characteristics. Pipe lengths, types, and diameters were transferred from the base map to the link-node system and were associated with each individual link number. Topographic data, in the form of the "upstream" and "downstream" node numbers for each link, were also recorded from the base map. This information about the system sets the convention for flow throughout the WSSM, as well as providing topologic connectivity. By convention, flow in the pipe from the upstream node to the downstream node is positive, and flow into a node is positive.

The coordinate locations of each node were digitized through hand takeoff from the gridded overlay and were recorded. Elevations were obtained by placing the overlay on the base map and reading the elevation at each node from the contours. (Contours on the base map are at 3-ft [0.9-m] intervals.) Data for both the links and nodes were encoded and prepared as input to the file establishment module of WSSM.

Development of demand data. Although metered information is available for the majority of the customers, demand data were developed for other than industrial users by performing "house counts" within demand zones. Demand zones were drawn on the link-node overlay to arbitrarily relate demands to nodes. Each node has a demand zone, and it is assumed that any demands falling within that area are aggregated to the node.

Development of cost data. At its current state of development, the economic allo-

Structure of link or node file for N elements
Header record
Element 1 record
Element 2 record
Element 3 record
Element N-2 record
Element N-1 record
Element N record
Structure of the record for an individual link or node element
Element number
Data fields for topological connectivity (cross-references between link and node files)
Data fields for spatial coordinates (location of node or ends of link)
Data fields for attributes (e.g., size, type, material, demand)
Working storage for user

Figure 3. File and record structure

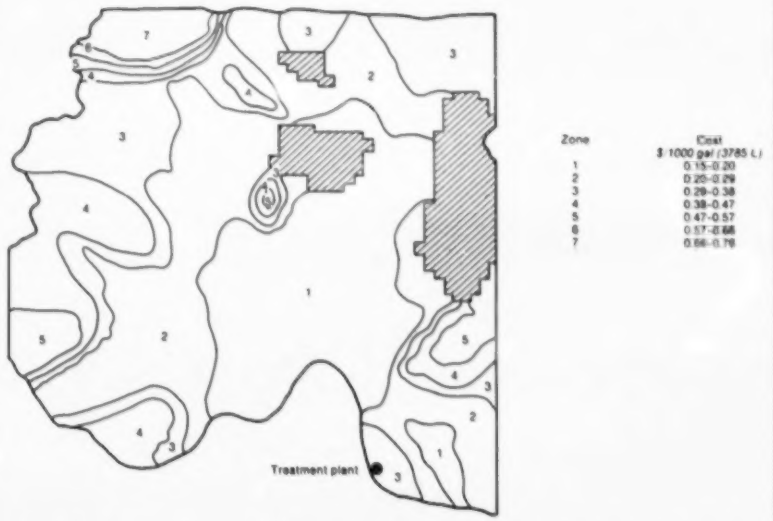

Figure 4. Cost contours for Cincinnati Water Works service area, based on WSSM[5] *(1973 costs)*

Figure 5. Map of New Vienna, Ohio

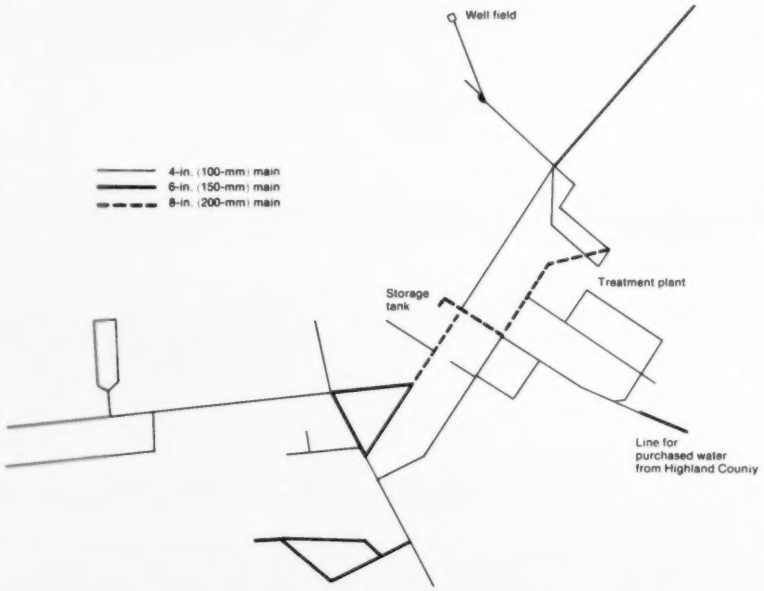

Figure 6. Schematic of New Vienna water supply system

cation procedure requires a single annualized cost, representing the combination of amortized capital and operation and maintenance (O & M) costs, for each node and link. For the case of New Vienna, actual construction costs were not available for most elements.[7] Capital costs, in general, were estimated as current (1981) replacement costs, which were then revised to actual year of installation through use of the three-digit *Engineering News Record* Construction Cost Index (CCI). Because the base year of the CCI is 1913, all system elements known to be installed prior to that date were treated as if they had been installed in 1913. Existing well and water treatment system costs were estimated based on cost curves derived from the publication "Estimating Water Treatment Costs."[7] Bid data for replacement of the elevated storage tank were used to estimate its cost. Pipe costs were based on unit prices in a construction bid for the area.

Annual O & M costs were taken from village records. Total O & M costs for 1981, including debt service and administrative costs, were projected to be $46 721. Cost summaries for the nodes and links showed the 1981 cost of construction, year of construction, CCI factor, original cost of construction (computed), and the 1981 O & M cost.

Use of WSSM for New Vienna

Once the basic description of the link-node network and its physical characteristics has been obtained, the data are encoded. These data are then used as input to the data base establishment programs, ESTBLINK and ESTBNODE. Program ERCHECK is run to test for topologic errors. At this point, it is frequently desirable to visually inspect the data base and to refer back directly to the base map. Accordingly, program NETPLOT is utilized to obtain a computer plot of the network at the desired scale. Program REPORTER also lists the data base, showing what information has actually been stored for each pipe and node.

Once the data base has been inspected and corrected, the hydraulic analysis module is used to determine pressures and flows for a given set of demands. The results are stored in the data base. Program NETPLOT is used to display these results (Figure 7), greatly simplifying the calibration process. Once an adequate hydraulic simulation is achieved, the solver module is used to determine costs, travel time, and nodal concentrations. Figure 8 is a computer-generated contour plot showing the unit costs of delivered water at the nodes of the New Vienna system.

It should be noted that WSSM does not provide answers, but rather is a tool for managing and displaying water

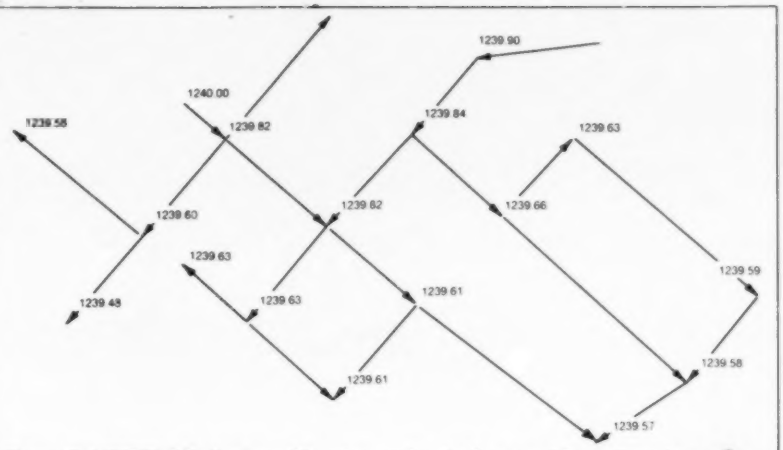

Figure 7. NETPLOT display of head at nodes (in feet) and flow direction

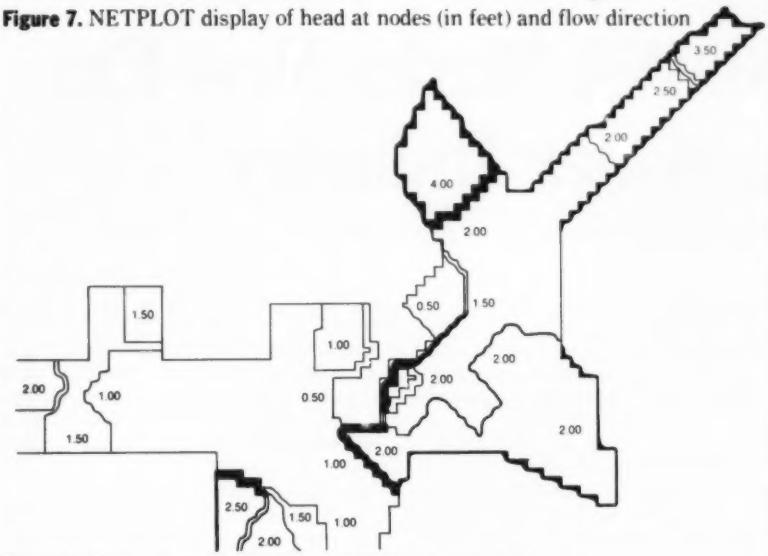

Figure 8. Cost contours ($/1000 gal [3785 L]) for New Vienna

supply network data. The WSSM technology is designed to aid the researcher, engineer, economist, and planner.

Summary and conclusion

The Water Supply Simulation Model can be used to provide spatial cost allocation, time of travel, and contaminant concentration information for a water supply network. Development of this model allows additional insight into the treatment and delivery of water. The approach employed in the WSSM is general in nature and is not restricted to water supply problems. In fact, the model should be applicable to the analysis of any service delivery system that can be characterized as a distribution network overlaid on some spatial distribution of supply and demand.

Some potential future studies of the WSSM include:

- exploration of the impact of design for fire protection and of the manner in which beneficiaries of this nonconsumptive use of water are assessed;
- further exploration of peak and off-peak considerations, and simulation of pricing strategies;
- use of the concentration and time-of-travel capabilities of the WSSM to simulate quality differences in multiple-source systems and to study the transport and decay of waterborne pollutants through the system;
- further examination of spatial methodologies for parameterizing hydraulic network analysis models in a simple manner;
- use of the graphic capabilities of the WSSM in other arenas, such as pipe break and water quality data; and
- examination of the effect of the water supply network on land development patterns and of the interrelationship between the water supply network and the waste collection network.

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